ADVANCED SEAL RIG EXPERIMENTS AND ANALYSIS

Roger Paolillo
Pratt & Whitney
East Hartford, Connecticut

2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis

NASA Glenn Research Center / OAI
Cleveland, Ohio
November 8, 2005
Turbine Seal Development Session

2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis
Topics for Discussion

- Advanced Sealing
  - Compliant
  - Non-Contact
  - Labyrinth seals
- Labyrinth Seals in Gas Turbines
  - Typical lab seal design parameters
  - Typical flow parameter correlation based on available empirical rig data
- CFD: Labyrinth Seal Physics Based Models
  - Validated with available empirical rig data
  - Evaluate additional geometric effects through sensitivity analyses
  - Evaluate additional aerodynamic effects through sensitivity analyses
- ASR rig
  - Tri-party agreement offers a win-win-win situation
  - Rig capabilities simulate engine operating conditions of surface speed, temperature, and pressure level
  - Accurate measurements of clearance and measured seal flow
- Test Articles
  - How related to analysis work
  - How modified for rig
- Test Results
  - Concave seal
  - Hammerhead seal
- Conclusions/Future Work

2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis
Rotating Seal options: Why Still Work On Labyrinth Seals

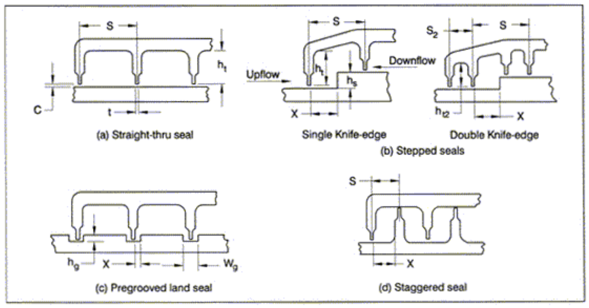
- **Compliant Seals eg. Brush Seals, Finger Seals**
  - **3-5X flow reduction**
  - **developing higher surface speed, temperature, and pressure levels**
  - **interference/debris/durability issues**
- **Non Contact Seals eg. Aspirating, Film Riding**
  - **5-10X flow reduction but still improving surface speed, temperature, and delta pressure levels**
  - **limited applications**
  - **interference issues**
- **Labyrinth Seals still the workhorse seal in gas turbine engines**
  - **long history of use in compressors, turbines, around bearing compartments**
  - **cheaper to make than many other seals**
  - **small improvement x many seals (up to 50*) = big gain in performance/operability**
  - **well and still investigated by academia & industry**
  - **with a proper abradable seal land can handle interference**

*NASA/TM 2004-211991/Part 1 “Turbomachine Sealing and Secondary Flows”
R, C. Hendricks, B. M. Steinetz and M. J. Braun

Why still work to reduce leakage of of labyrinth seals.

Still the workhorse seal in gas turbines

2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis
Empirical Labyrinth Seal Analysis Model based on '70's Rig Tests & Literature Data



Lab Seal Flow; $W = \phi\alpha\gamma K_1(Pu / Tu^{1/2})\,A$

Where:

ϕ	= flow parameter, f(#KE)
Tu	= upstream temperature
Pu	= upstream pressure
A	= area based on seal clearance
α	= discharge coefficient, f(C,t, KE tip radius)
γ	= carry over factor, f(C,S, hs, pressure ratio)
K_1	= land porosity eg. honeycomb land, f(C)

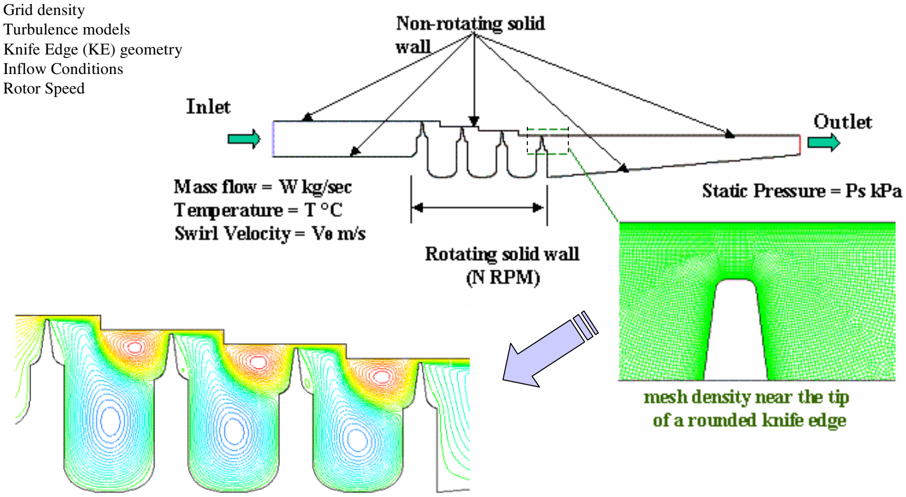
Labyrinth seal design system based on seal's leakage from the early '70's from gas turbine engine testing and rig testing

All empirically developed design systems

2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis

CFD Sensitivity Studies Developed A Physics Based Lab Seal Model That Could Predict Rig Data & Literature Results Reasonably Well

Sensitivity Studies Included:
- Grid density
- Turbulence models
- Knife Edge (KE) geometry
- Inflow Conditions
- Rotor Speed



Labyrinth Seal Stream Contours

Advent of CFD maturity has provided a physics based modeling approach to assessing seal leakage

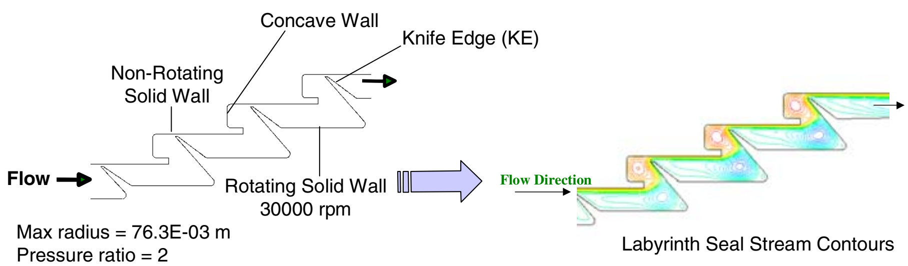
The CFD models must be first validated with the available test data before these seal models can be used to explore leakage reduction designs.

2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis
CFD Lab Seal Model Used to Assess Sealing Effectiveness of Canted KE Configurations

Stocker advanced labyrinth design which showed 20-25% seal flow reduction were modeled as starting point.
Optimization studies were performed on the following parameters:

- step height
- step shape
- KE angle
- KE axial position
- Rotor Speed

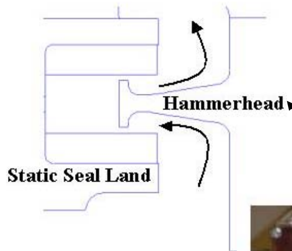
In limited optimization studies no labyrinth seal design was found better than the initial Stocker configuration



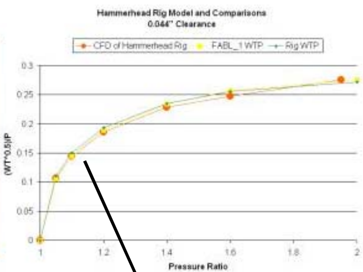
Max radius = 76.3E-03 m
Pressure ratio = 2
All walls are adiabatic

Best leakage reduction concepts found in the literature are evaluated with validated CFD models
2D axisymmetric CFD models sensitivity studies did not improve upon existing design concepts

2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis
Empirical & CFD Labyrinth Seal Models Matched Static Cold Flow Testing of Baseline Hammerhead Seal Design



Hammerhead seal is basically a compact labyrinth seal design



CFD model & Lab Seal flow parameter model match static cold flow results

The hammerhead seal design is an attempt to minimize the geometric design space needed for multiple knife edged labyrinth seals

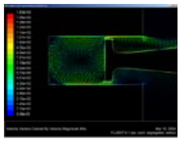
The hammerhead seal design also attempts to maintain a tight clearance for one set of knife edges at all times of gas turbine engine operation

Initially the seal is modeled as a conventional labyrinth seal of the same number of knife edges.

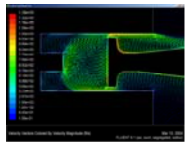
Static cold flow tests confirm this modeling approach.

2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis

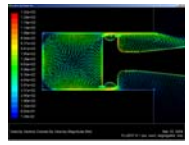
CFD Hammerhead Model Used to Assess Sealing Effectiveness of Various Configurations



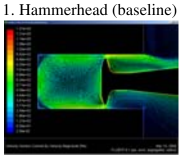
1. Hammerhead (baseline)



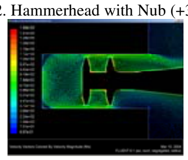
2. Hammerhead with Nub (+3%)



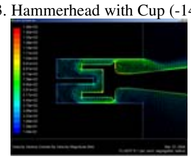
3. Hammerhead with Cup (-14%)



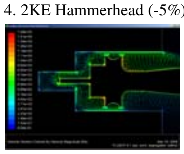
4. 2KE Hammerhead (-5%)



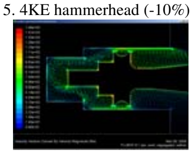
5. 4KE hammerhead (-10%)



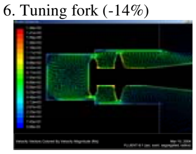
6. Tuning fork (-14%)



7. Inverse tuning fork (-33%)



8. Mod Inverse tuning fork (-20%)



9. 4KE Stepped hammerhead (-24%)

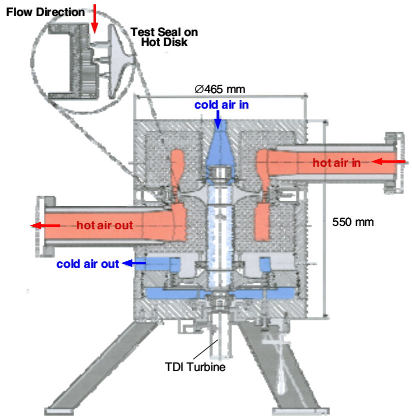
Trial 1 matches static cold flow tests
Trial 2 is the 2KE hammerhead seal tested in ASR
Trial 9 is the 4KE hammerhead seal tested in ASR
Trial 7 has highest effectiveness; shows benefit of tight clearances forcing air through tortuous paths

CFD modeling is used as an analytical test tool to explore best leakage design concepts

As expected, if it behaves like a labyrinth seal then the same leakage reduction features work best (more knife edges, stepped seal lands)

2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis

Advanced Seal Rig (ASR) Designed & Built to Test Seals at Engine Operating Conditions



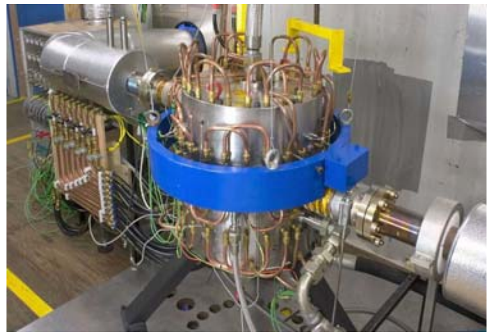
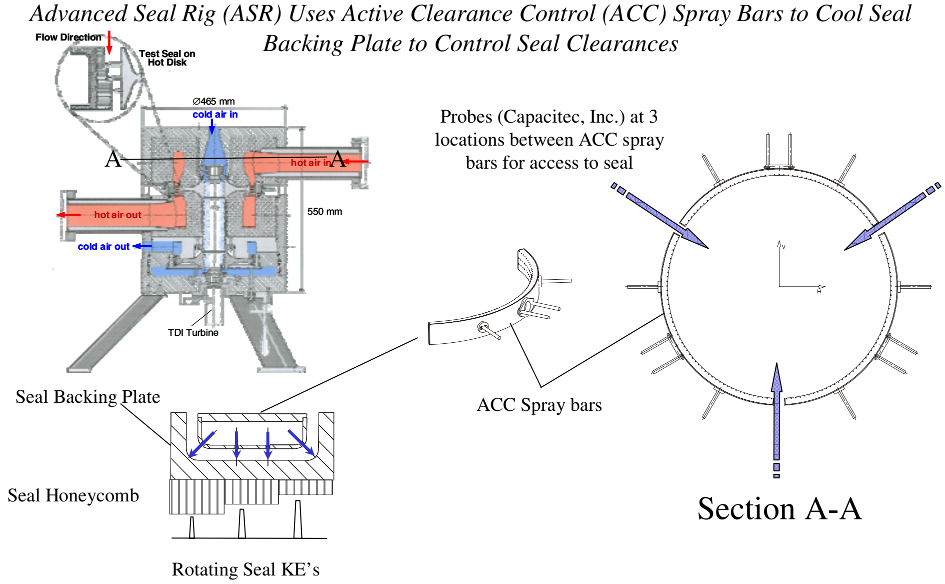


Table 1. Functional requirements		
Parameter	Specification values	
	ISO-units	USA-units
Gas temperature upstream	20 - 815 °C	70 - 1500 °F
Gas pressure upstream	12.0 – 24.1 bars	175 – 350 psi
Gas pressure difference	1.0 – 7.0 bars	15 – 100 psi
Diameter disk	254 mm	10 inch
Rotational speed	Static – 365 m/s	Static – 1200 ft/s
Seal gap width	0.1 – 0.4 mm	3.1 – 15 mils
Mass flow	0.04 -.8 kg/s	0.09 – 1.6 lb/s

Rig developed at the National Aerospace Laboratory (NLR) in The Netherlands to test advanced seal concepts at near gas turbine engine operating conditions.

2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis

Advanced Seal Rig (ASR) Uses Active Clearance Control (ACC) Spray Bars to Cool Seal Backing Plate to Control Seal Clearances



A clearance control design feature utilizes external spray bars to impinge cold shop air on the outer diameter of the test seal static backing plate to radially move the test seal land inward to the desired seal clearance.

Three equally circumferentially spaced probes (Capacitec, Inc.) are installed measure seal clearance and determine the level of active clearance control air needed.

2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis
Advanced Seal Rig (ASR) Typical Test Plan to Simulate Engine Operating Conditions

Test Point	Temperature	Upstream Pressure	Pressure Ratio	Speed (rpm)	Clearance
1	Low Temoperature 400C (750F)	Low Pressure 12 Bar (175 psia)	Pr 1.1	rpm 3500	Clr .38mm (.015")
2					Clr .25mm (.010")
3					Clr .127mm (.005")
4				rpm 15000	Clr .38mm (.015")
5					Clr .25mm (.010")
6					Clr .127mm (.005")
7			Pr 1.25	rpm 3500	Clr .38mm (.015")
8					Clr .25mm (.010")
9					Clr .127mm (.005")
10				rpm 15000	Clr .38mm (.015")
11					Clr .25mm (.010")
12					Clr .127mm (.005")
13			Pr 1.40	rpm 3500	Clr .38mm (.015")
14					Clr .25mm (.010")
15					Clr .127mm (.005")
16				rpm 15000	Clr .38mm (.015")
17					Clr .25mm (.010")
18					Clr .127mm (.005")
19			Pr 1.80	rpm 3500	Clr .38mm (.015")
20					Clr .25mm (.010")
21					Clr .127mm (.005")
22				rpm 15000	Clr .38mm (.015")
23					Clr .25mm (.010")
24					Clr .127mm (.005")

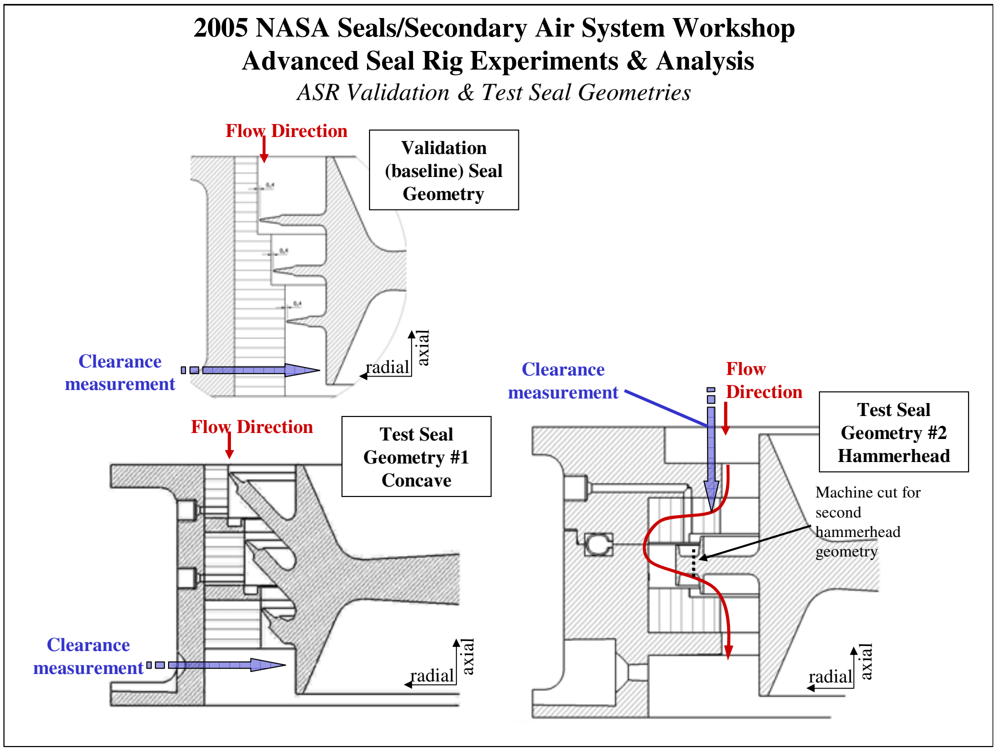
Set upstream temperature and pressure

Adjust downstream pressure to achieve pressure ratio

Set speed

Use ACC to obtain desired clearance

The seal rig can independently vary temperature, pressure, pressure ratio, speed, and seal clearance.

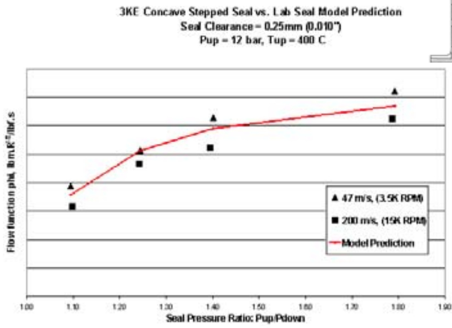


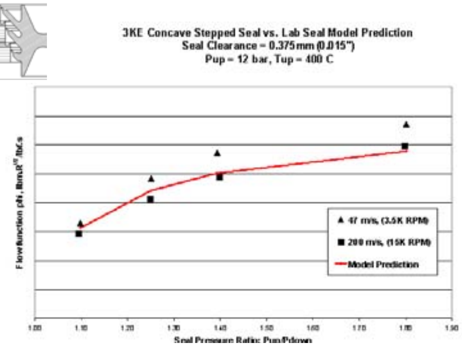
The baseline seal geometry was used to validate the rig. The baseline seal is a standard 3 knife edge stepped seal configuration that is typically found in many gas turbine engines.

Rig data matched within 10% the lab seal design predictions (AIAA-2005-3092).

The advanced lab seal design test results would then be assessed against both the existing lab seal design system predictions and against the baseline seal data.

2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis
Concave Seal Compared Well to Empirical Lab Seal Model

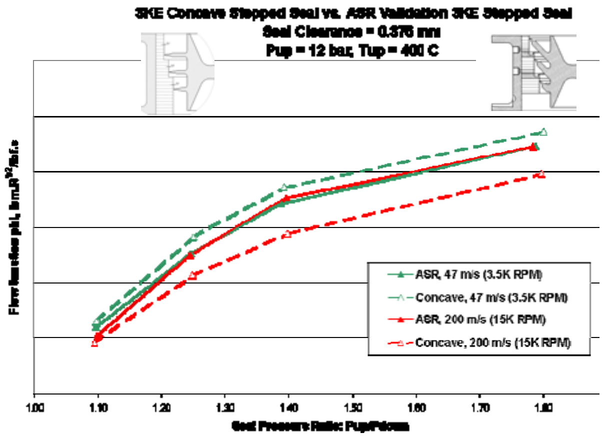




- **One empirical labyrinth seal model prediction (no rotational variation)**
- **Concave seal flow reduction with increasing rotational speed**
- **Comparisons with the lab seal model predictions show reduction is apparent (8%) only at the tighter clearance test point**

Concave seal test data compared well with the lab seal design system predictions.

2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis
Concave Seal Compared to ASR Validation (Baseline) Lab Seal

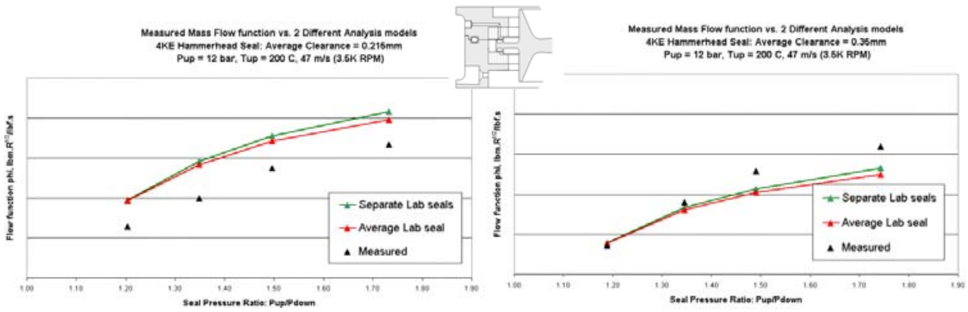


- **ASR Validation seal confirms no rotational variation**
- **Concave seal flow is reduced by 10% between 3500 & 15000 rpm test points**
- **Concave test at low speed has negligible rotation benefit; should equal ASR seal flow**
- **Higher concave seal flow at 3500 rpm probably due to 3X increase in KE to Step distance**

Concave seal test data compared to baseline seal clearly shows a rotational effect that reduces seal leakage.

2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis

4KE Hammerhead Seal Compared to Empirical Lab Seal Models Shows Additional Restriction at Tighter Clearances

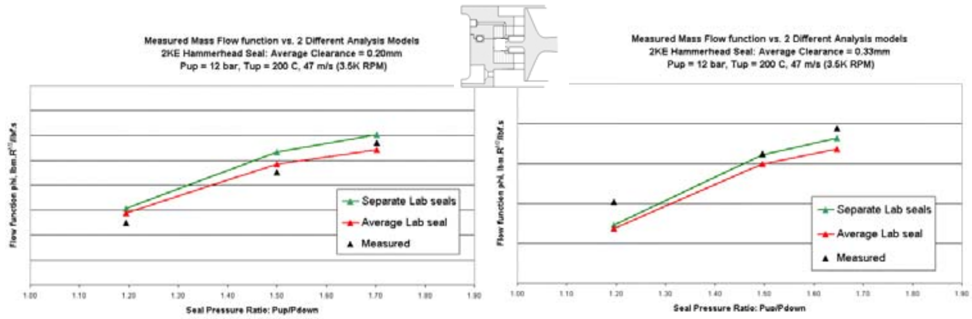


- **Empirical labyrinth seal model predictions show minimal change due to different clearances between upstream and downstream hammerhead knife edges**
- **Tighter hammerhead seal clearances introduce additional restriction of air through the seal than is accounted for in the model prediction**

4KE Hammerhead seal compared to empirical design system labyrinth seal model (4 knife edge stepped seal) shows additional restriction effect at the tighter clearances test condition. “Stretching out” hammerhead seal into an elongated staggered labyrinth seal type configuration possibly providing additional flow path restrictions.

2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis

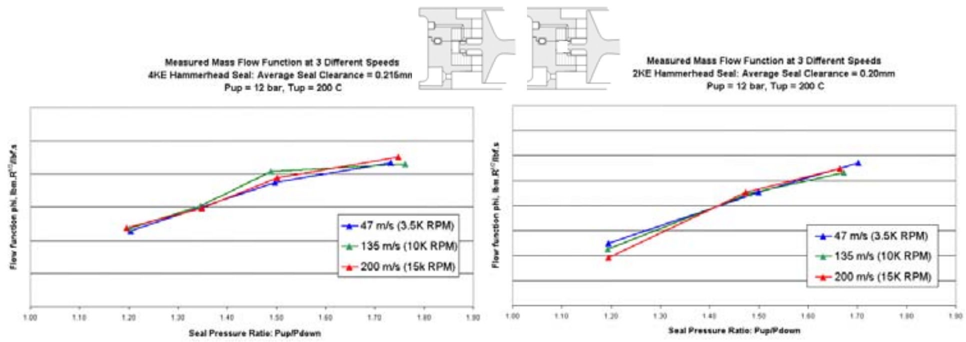
2KE Hammerhead Seal Compared to Empirical Lab Seal Models



- **Empirical labyrinth seal model predictions show change due to different clearances between upstream and downstream hammerhead knife edges**
- **Larger hammerhead seal clearances do not introduce much additional restriction of air through the seal than is accounted for in the model prediction**

2KE Hammerhead Seal Compared to Empirical Lab Seal Models
Staggered restriction benefit with tight clearances is lost with the reduction in number of knife edges

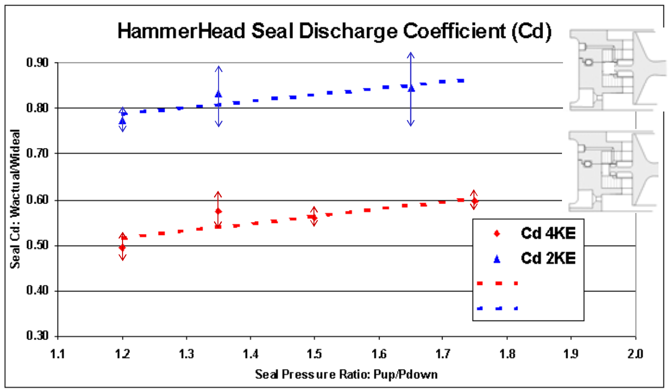
2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis
4KE & 2KE Hammerhead Seals Show No Rotational Effect



- **Hammerhead Seal Test Results Show No Influence of Rotational Speed**

4KE & 2KE Hammerhead Seals Show No Rotational Effect

2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis
4KE & 2KE Hammerhead Seal Discharge Coefficient Comparison Matches Trend Predicted by CFD Models



- **Comparison of Discharge Coefficients Show that the 4KE Hammerhead Seal to be at least 25% more effective than the 2KE Seal**
- **These Results are in Line with the Hammerhead Seal Design CFD Sensitivity Studies (Trail 4 vs. Trial 9)**

4KE & 2KE Hammerhead Seal Discharge Coefficient Comparison Matches Trend Predicted by CFD Models

Arrows show data scatter but trend is still apparent.

2005 NASA Seals/Secondary Air System Workshop
Advanced Seal Rig Experiments & Analysis
Conclusions/Future Work

- CFD Modeling, Validated With Existing Rig Data, Used to Define New Seal Designs with Seal Reducing Features
- An Advanced Seal Rig is Available to Test Seals at Engine Operating Conditions
  - Phase 2 plan underway to extend rig capabilities to 365 m/s & 815°C by end of 2005
- Test Data Suggests that Concave Seal Flow is Reduced with Increasing Rotational Speed
  - Additional testing at higher speeds planned
  - A second canted seal design with seal angles reversed (with flow direction) planned
  - 3D CFD analysis planned to investigate concave seal features providing rotation benefit; modeling of honeycomb cell structure will be included
- Empirical Labyrinth Seal Model Requires Updates for both Rotational and Axial Spacing Between Knife Edges and Steps
  - Testing planned utilizing baseline validation seal for different axial spacings
- Test Data Shows that Hammerhead Seal Flow Does Not Change with Rotational Speed
- Hammerhead Seals are Basically a Compact Seal that Behaves Like a Labyrinth Seal; Seal Flow is Reduced with More Knife Edges and Steps Between Knife Edges
- Maintaining Tight Clearances Between the Hammerhead Seal and its Static Land Will Reduce Seal Flow by Forcing Air to Travel Through a More Tortuous Path